Maritime Transport of CO_2

TEKNOLOGISK INSTITUT

MAERSK BROKER ADVISORY SERVICES

Maritime Transport of CO_2

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Table of Contents

Preface

This report was created based on the wish to explore and map the commercial opportunities for maritime transport of CO_2 from a Danish perspective. The publishing of this report has been made possible thanks to the Danish Maritime Fund's grant scheme, which aims to ensure financial support for initiatives that contribute to promoting Danish shipping and maritime industry. The project lasted from April 2022 to October 2022 in collaboration between Maersk Broker Advisory Services and the Danish Technological Institute. Thus, a great appreciation and recognition must be extended to the Danish Maritime Fund's mission and work to make this project possible and support the promotion of new potentials.

The report is a preliminary study and will include a mapping and detailed description of relevant commercial and technical problem areas regarding the use of ships for transportation of CO_2. The preliminary study will, among other things, describe the volume, rates, contract types, competing alternatives for transportation and infrastructure. Technological, political, and environmental considerations will also be included in the preliminary study. This report will be the first of its kind to focus on the commercial mapping of a value chain from a maritime and northern European perspective. The report includes several expert interviews from different actors in the Carbon Capture Utilization & Storage (CCUS) value chain, which include key points and insights from all parts of the value chain.

The report is structured as follows: it begins with a short background description of Carbon Capture Utilization and Storage (CCUS) and its potential interaction with maritime transport highlighting the purpose of this report and presenting the issues to be answered in this report. Then, the methodological approach is described by presenting the report's underlying hypotheses intended to ensure coherence and guidance in this report. After this, the report goes through chapters that deal with the collected empirical data on volumes, pricing, alternatives/barriers, and the role of maritime transport in the value chain. Lastly, a conclusion is provided that partly concludes the report and highlights the future role of Danish shipping within the CCUS market.

Project's steering committee:

- Daniel Asger Cáceres Larsen, Maersk Broker Advisory Services
- Jacob Ask Hansen, Danish Technological Institute
- William Norvold Bjørn, Maersk Broker Advisory Services

In addition, the following project participants contributed to this project:

- Kim Winther, Danish Technological Institute
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- Anna Zink Eikeland, Danish Technological Institute

1. Background and Aim

The energy sector is in the middle of a major green transformation that will reduce the emissions of fossil energy sources. It is not expected that a complete independence of fossil energy sources can be achieved, which is why reducing CO_2 emissions is not sufficient on its own. The International Energy Agency (IEA) has selected Carbon Capture, Utilization and Storage (CCUS) as one of the key technologies that must help to ensure economic sustainability in the energy system in connection with the green transition and the opportunity to achieve the future climate goals.[1]

In connection with the expansion of CCUS in Denmark and the neighboring countries, the need for the transportation of CO_2 is expected to increase significantly. The CO_2 must be transported from capture facilities or the nearby ports to storage facilities or CO_2 consumers for utilization, for example, to Power-to-X (PtX). The transportation of CO_2 is an intermediate link in the CCUS chain and can be done using pipelines, land transport or maritime ship transport, depending on, e.g., the geographical location and the volume of discharge. The value chains in connection with CO_2 capture, storage and utilization are still being developed, and the maritime transport of CO_2 is expected to have a great importance hereof. This is partly due to the flexibility associated with maritime transport, which can or will become necessary for the establishment of value chains, and partly to an expectation that not all storage or application facilities will have volumes and distances to sources that justify the establishment of, e.g., pipelines.

In this report, maritime transport will refer to the transportation of CO_2 by ships specifically designed for this purpose. Maritime transport of CO_2 is not expected to result in a greater technical complexity compared to the transport of other gases such as Liquified Petroleum Gas (LPG) or Liquified Natural Gas (LNG). This means that the design of ships will be founded in verified technology, and this would not cause technical challenges that would hinder or make the transportation of CO_2 by ships impossible. If we look at the land infrastructure required to support the shipping of CO_2, no major technical challenges are expected here either, as it will remind of previously established value chains, for example, the global LNG market. Already now, there are a few ships for the transportation of CO_2, but they are too small for the future needs.

Hence, it is relevant to investigate the underlying commercial potentials within maritime transport of CO_2 to see if there is a market for it. In this report, this potential will be illustrated upon value chain considerations with an aim to map the relevant problem areas around this topic:

- Identification of major stakeholders throughout the entire value chain from CO_2 source via capture and transportation to storage or utilization.
- Estimation of potential volumes to be transported.
- Estimation of the possible market price for maritime transport of CO_2 and the entire value chain.
- Estimation of the potential of maritime transport of CO_2 with a focus on Danish shipping.

[1] International Energy Agency; Global Energy Review: CO_2 emissions in 2021

2. Summary

Through series of interviews with key stakeholders within CCUS in Denmark and the neighboring countries, existing experience with transport routes for CO_2 and expectations for future development will be revealed. The relevant aspects such as time, costs and possible financial gains are described below.

The data acquired in the interviews resulted in the following key statements:

- CCUS is expected to play a significant role in the phasing out of fossil fuels from industrial plants and is closer to making commercial sense with the increasing CO_2 taxes in both Denmark and Europe.

- The first commercial projects are expected to be in operation before 2030, and it is expected that there will be enough storage capacity for the planned capture of CO_2 both in Denmark and Europe.

- Maritime transport can become a competitive and flexible method for transporting CO_2 from the emitting facility to storage facility and can play an important role in establishing an effective CCUS value chain in the North Sea. To make the maritime transport of CO_2 possible, it is necessary to establish additional infrastructure, and the project must be optimized across the value chain to be able to attract long-term capital.

- The price for maritime transport is relatively a small part of the total costs across the value chain, where the capture of CO_2 constitutes the largest part of the price. Both capture and transportation are expected to be reduced significantly by the scale and maturity of projects.

- There are no ships yet that are ready to transport CO_2, and they are only built or financed if the shipowners can secure long-term contracts.

- In the short term, before 2030, the market will be based on long-term contracts between predefined capture and storage facilities. There is no indication that the utilization of CO_2 will have a significant role in the CCUS value chain in the short term.

- In the long term, after 2030, it will require a larger scale and several locations for capture, storage, and utilization, if the market for maritime transport of CO_2 is to be established. Many existing shipping companies will have the competences to join this market that may result in a less attractive market with a great price competition.

- The fact that the use of CO_2 will not play an important role in the short term is because the value chain for its utilization is not ready. In the long term, a market could potentially emerge for utilization, where biogenic CO_2 is transported to places with inexpensive electricity to produce synthetic fuels. Here, the maritime transport could play a significant role.

- Danish actors are currently among the first movers, but if they are to have an advantage staying in this position, it requires that the Danish CCUS projects are established as quickly as possible and preferably before our neighbors at the North Sea.

3. Applied Methodology

Based on the existing knowledge, this report follows a hypothesis-driven approach with an aim to clarify the business potential for maritime transport. Thus, the following hypotheses have been defined:

- In the short term, there is a market for maritime transport of liquid CO_2 from capture to storage.
- In the long term, there is a market for transport of liquid CO_2 from capture to storage and utilization.
- Maritime transport is competitive with alternative forms of transportation.
- Subsidies and/or other forms of legislation are necessary to commercialize the value chain due to limited willingness to pay by recipient and emitter.

According to these hypotheses, the value chain is uncovered by collecting input from relevant parties. Here, a questionnaire is created for the first interview series. Based on the conducted interviews and the wish to acquire additional information to further resolution of the hypotheses, the questionnaire and focus on the value chain are evaluated in a second series of interviews focusing on the maritime actors and relevant opportunities and challenges.

Since it requires considerable technical and economic insight to assess the future CO_2 market, the interviewed parties are carefully selected experts who represent the entire value chain, still with a special focus on sources, capturing and shipping.

3.1. Value Chain

The value chain around CCUS consists of several interdependent actors and is currently quite immature. The first link in the value chain is related to the collected CO_2. It can be the owner of a source that emits CO_2, for example, an industry or biogas plant, or CO_2 collected directly from the surrounding atmosphere containing approx. 0.05% CO_2. The emitted CO_2 is captured with a Carbon Capture technology (CC-technology), after which it is stored locally (short-term storage) or is led via pipelines to a remote storage. The suppliers of CC-technology are the next link in the value chain. Thereafter, the CO_2 is transported to a port, either by a tanker or a pipeline. The truck driver or owner of the pipeline thus becomes the next link in the value chain. At the port, there are facilities that allow the CO_2 to be loaded onto a ship. Thus, both ports and shipowners are separate links in the value chain. The ship destination may either be a port or a depot in the underwater underground. Upon arrival at the port, there are two options for further shipping of the CO_2: it can either be led to a plant for usage of CO_2, for example, PtX (Utilization), or it can be led to a depot in the land-based underground (Storage). If the ship's destination is the underwater underground, it would sail, for example, to a former oil field and pump the CO_2 down into a depot (Storage).

It is crucial that each link in the value chain includes a commercial element, otherwise the chain will be broken. Thus, the earnings in each value chain link constitute a prerequisite for the entire chain. To illustrate this, experts have been selected from companies who 1) represent individual links in the overall value chain, or 2) have extensive knowledge about the entire value chain. These links together with the selected companies have been illustrated in Figure 1.

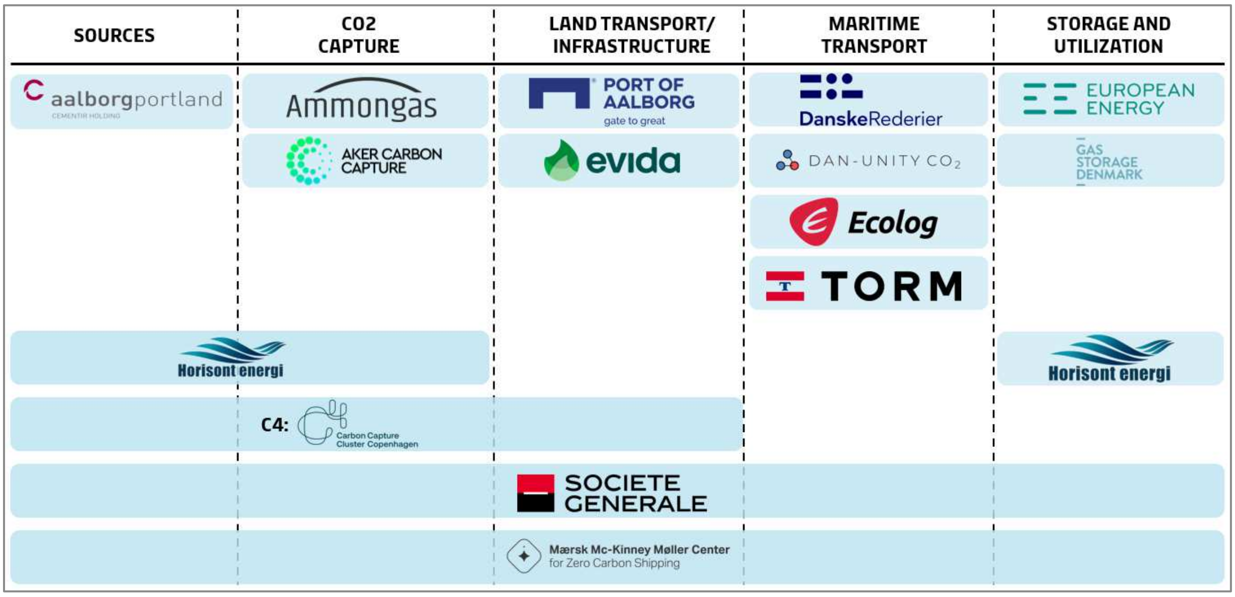

Figure 1: The 5 main elements in CCUS value chain including the placement of the interviewed companies in the value chain.

3.2. Framework of the questionnaire

According to the established hypothesis, the questionnaire framework has been created based on four headings: "Volumes", "Price", "Alternative", and "Obstacles" as outlined in Table 1. Since the value chain contains different actors with different roles, the questionnaire is designed in a way that each respondent can express his/her expectations to that part of the market which they are most familiar with. This is to avoid guessing and repetition of expectations, which have already been mentioned in the media. The industry is also characterized by fierce competition of becoming the *First Mover,* which means that there are important trade secrets at stake. Therefore, the respondents cannot always provide concrete comments on prices and costs, as this is competitively sensitive information. The questionnaire has taken this into account by allowing the respondents to choose to answer for their own company or sub-process, industry branch or region. Their answers are an expression of the respondent's own *expectations* at the time of the interview and are thus not actual figures. The interview round 1 was conducted from April to June 2022, while interview round 2 was conducted in August 2022.

The interview guide for the first and second round can be found in Appendix 1, Table 7 and Table 8, the list of respondents can be found in Appendix 2, Table 9.

Table 1: Foundation for questionnaire

Volumes	Price	Alternatives	Challenges
How much CO_2 must be captured?	What are the costs for storage?	What other plans are there for transportation of CO_2?	Legal framework (permits for import/export)
How much CO_2 is expected to be stored?	What are the costs for capture?	What are the plans for capture and utilization of CO_2?	Financial framework (subsidies/taxes)
What is the time frame for capture and storage?	What other costs are connected to maritime transport? • Infrastructure • Land transport	Who are the competitors for maritime transport?	Infrastructure at ports (how generic can this infrastructure become?)
Is maritime transport envisioned in relation to the currently financed projects?	What will be the value of a ton of CO_2? • Taxes / Subsidies		Necessary technology maturation (time frame?)

4. Assessment of quantities

To assess the volumes of CO_2 to be transported by ship, it is both relevant to assess the volumes that will be necessary to capture in the Danish and European context, and to assess the quantities that can be stored in, e.g., the North Sea. The gap between theoretical assessments and the implementation of infrastructure as well as capture and storage can be very wide. This, among others, is attempted to be clarified through interviews. In relation to assessing the potential of maritime transport of CO_2, it is not only important to consider the timeline for the implementation of capture of CO_2, but also the alternatives for storage and the possible infrastructure around this.

If Denmark is to reach the target of 70% reduction in CO_2 emissions by 2030, a reduction of 9.4 Mtpa CO_2 is required compared to the current emissions. A part of this is expected to take place via CCUS, where the climate council estimates the quantities to be stored from Denmark to approx. 4.5 Mtpa in 2030. The potential for CO_2 for Danish storage is, however, considerably greater, as the Danish government, among others, sees Germany, Sweden, Belgium, and Finland to have a significant potential for exporting CO_2 (regarding storage) to Denmark. In its "Assessment of the market potential for CO_2 storage in Denmark", the Danish Energy Agency estimates that the potential for import of CO_2 for storage is up to 45 Mtpa.[2] International Energy Agency (IEA) estimates that CO_2 emissions worldwide must be reduced by 36.3 Gtpa[3], where CCUS have been mentioned as one of the key technologies to achieve this. It is estimated that 840 Mtpa will be captured in 2030, where 640 Mtpa are expected to be stored and the rest utilized. In 2050, it is expected that 5,600 Mtpa will be captured and 5,230 Mtpa will be stored.[4]

[2] Assessment of the market potential for CO_2 storage in Denmark, Danish Energy Agency, May 2021
[3] International Energy Agency; Global Energy Review: CO2 emissions in 2021
[4] International Energy Agency; Energy Technology Perspectives 2020 – Special report on Carbon Capture Utilization and Storage

4.1. Expectations to CO_2 capture

To be able to illustrate the volumes of CO_2 expected to be captured and stored both in the short and long term, several actors with different positions in the value chain have been selected having knowledge about expectations to Danish CCUS plans, especially about the volumes relevant for capture and storage. In Denmark, some of the largest point sources have concrete plans to capture CO_2 for storage, while a large part of other large sources is centered into five clusters around Copenhagen, Aalborg, Aarhus and Fredericia[5]. In addition, there are several smaller sources from which CO_2 must be captured in the long term. Here, biogas plants are especially interesting, as many of these are already upgrading biogas by separating CO_2 from the extracted gas. Additionally, the CO_2 collected from biogas plants is biogenic, and will thus be relevant for utilization in, for example, production of synthetic fuels via PtX. Synthetic fuels, also called electro-fuels or e-fuels are liquid fuels that are based on sustainable energy and are seen as the solution to the green transformation of the transport sector.

The responses collected in the interviews with Danish actors indicate that many of the short-term plans (1-5 years) are based on the current and future tenders from the Danish Energy Agency in relation to the capture of 400 ktpa in the current and 500 ktpa in future tenders. It is worth noting that only one consortium is expected to be able to access these funds. The short-term plans for capture and storage must thus be seen in this connection. However, the great interest in these tenders indicates also concrete plans for several actors in connection to capture and storage of CO_2. There is no doubt, however, that there are plans that go beyond the current tenders and that in the long term these will give rise to considerably larger volumes of captured CO_2 for storage.

Already now, there are concrete plans for capture to storage from Aalborg and Copenhagen in 2030. Aalborg area has the potential for capturing to storing of up to 1Mtpa from Aalborg Portland, and more capture for shipping from Aalborg Port of approx. 3 Mtpa. From the Copenhagen area, Carbon Capture Cluster Copenhagen (C4) is expected to capture up to 3 Mtpa from the 6 partners.

In addition to these concrete initiatives for capturing from large point sources, there are also plans for capturing CO_2 from biogas plants. Here, EVIDA expects capturing 1.5 Mpta from biogas, where Ammongas expects that a plant with a capacity of 2 Mtpa will be installed for biogas before 2030, and a further 1 Mtpa is expected to be captured from waste incineration.

These figures match the expectations from the Danish Energy Agency on the potential of CCUS between 4.9 Mtpa and 9 Mtpa. However, these figures are subject to uncertainty and some overlaps, and they fail to represent the full potential of CCUS, where significant volumes can also be expected from, e.g., Aarhus area.

These observations are only valid for capture in Denmark expected to be carried out before 2030. Additionally, large quantities of CO_2 are also expected to be captured and handled, especially from Germany, the Netherlands, Poland, UK, and Norway. From Norway, the volumes are expected to be the same as from Denmark, while from Germany and Poland the CO_2 volumes can be expected in the range from 12-16 Mtpa. From UK, storage of 20-30 Mtpa is expected from 2030.

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[5] Danish Energy Agency: Punktkilder til CO2 – potentialer for CCS og CCU

4.2. Expectations to storage of CO_2

In Denmark, there are primarily three existing projects for storage of CO_2: Offshore projects Greensand (INEOS) and Bifrost (Total Energi), and onshore storage on Zealand (Gasstorage Denmark). Also, the Norwegian project Northern Lights is localized, so it will become relevant in relation to storage of CO_2 from Denmark. Northern Lights is the most advanced project with expected CO_2 storage of 1.5 Mtpa from 2023, and 5 Mtpa in the future. In Greensand, a license has just been acquired for test storage of CO_2, and it is expected to be able to store up to 1.5 Mtpa from 2023, and 6-8 Mtpa from 2030. Total Energi have started the Bifrost project and plan to store 3 Mtpa in short term and up to 10 Mtpa in long term. Furthermore, it is estimated that 500-1,500 ktpa of CO_2 can be stored on land from 2028.

In addition to the mentioned ongoing storage projects in Denmark and Norway, the Netherlands and UK are particularly active in establishing CCUS infrastructure and storage facilities.[6] In the Netherlands, in Porhos and Aramis projects, CO_2 hubs will be established around Rotterdam with pipelines for off-shore storage with an expected capacity of approx. 10 Mtpa. The stored CO_2 is expected to originate partly from the capturing field, but also from the neighboring countries, from which there are good transportation opportunities by ship or barge via the European canal systems.

UK has also several projects for the establishment of CCUS, among others, "Zero Carbon Humber" with planned storage of 9.5 Mtpa, while "Netzero Teesside" plans to store 10 Mtpa. Furthermore, in the project "Acorn" the existing infrastructure is used to establish an offshore CO_2 storage of 5-10 Mtpa. Just like in Denmark, also in UK, licenses are currently offered for storage of CO_2 with an aim to store between 20 Mtpa and 30 Mtpa of CO_2 in 2030.[7]

The projects in the Netherlands, Norway and UK currently constitute a large part of the CCUS storage infrastructure that has already been established or will be established within a relatively short period of time. Horisont Energy plans offshore CO_2 storage of 2-6 Mtpa in the Polaris project in the Barents Sea, and 4-8 Mtpa during the first development stage in Errai Project, which is developed in collaboration with Neptune Energy. Also, Altera and Aker are planning to store 10 Mtpa in Stella Maris.

In Iceland, Carbfix is already active as to the mineralization and storage of CO_2 and has already now stored approx. 85k tons. The established projects have a limited storage rate of approx. 50 ktpa, but with their plans to establish "The Coda Terminal", the capacity of CO_2 storage at Carbfix will increase to 3 Mtpa in 2031.

As previously mentioned, the total capacity in Danish underground is considerably larger than the quantities of CO_2 expected to be captured in Denmark before 2030, whereas there will be a need for storage capacity for CO_2 captured specifically in central Europe. This could be done in the Danish underground, but this has a direct competition with storage projects in the British part of the North Sea, the Netherlands, and in Iceland.

[6] https://iogpeurope.org/wp-content/uploads/2022/01/Map-of-EU-CCS-Projects-January-2022.pdf
[7] https://www.nstauthority.co.uk/licensing-consents/licensing-rounds/carbon-storage-licensing-rounds/#tabs

However, the amount of CO_2 to be stored is not solely determined by the amount of CO_2 to be captured. It is expected that in a few years it will become necessary to use CO_2 for PtX. Here, the production of synthetic fuels should be considered. Currently, the facilities for this are rather immature, and the first ones are expected to be ready in 1-5 years. Through the conducted series of interviews, plans for the usage of approx. 1-2 Mtpa in Denmark have been identified, focusing on the usage of CO_2 from biogenic sources. The focus on these sources is primarily due to two aspects: 1) some buyers of synthetic fuels require that the CO_2 to be used is green, and 2) there is no financial incentive structure today to support the storage of biogenic CO_2.

Since there are some time delays between the need for biogenic CO_2 and the need to implement CO_2 capturing at sources that emit biogenic CO_2, it is expected that this CO_2 will also have to be stored until sufficient demand for CO_2 for PtX is established. Several respondents have expressed doubts to whether it will make sense in the long term to produce synthetic fuels via PtX in Denmark, as this production requires access to large quantities of cheap energy. In the long run, this can be solved by expanding the green electricity infrastructure in Denmark, or by shipping the captured CO_2 to areas with access to inexpensive energy.

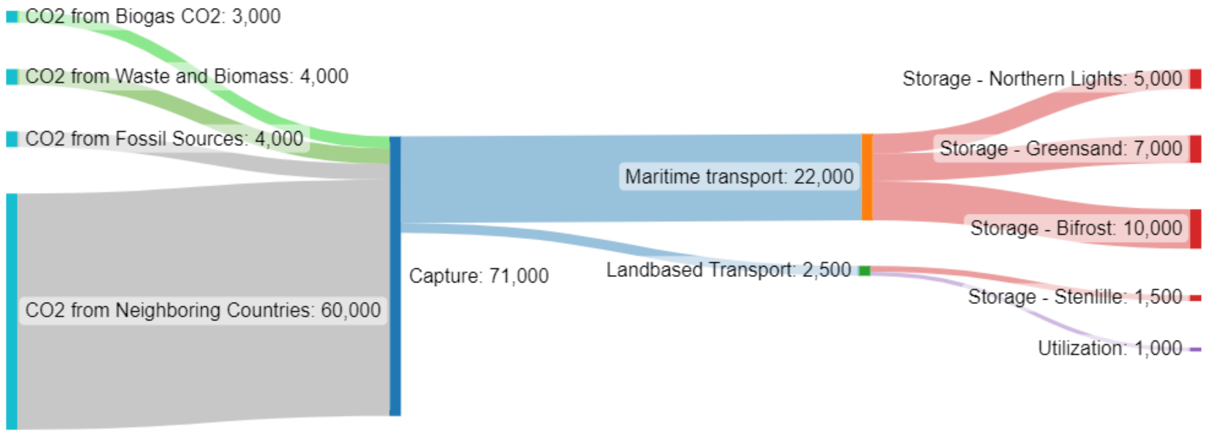


Figure 2: Schematic overview of planned volumes of CO_2 from a Danish perspective, towards 2030, through the value chain from emission to capture and transportation and to storage and utilization.

5. Pricing

When looking at pricing, it is necessary to consider the entire value chain from emitter to storage. For a CCUS to make commercial sense, the total costs in this entire value chain must be covered by those tax and quota savings that are there from not emitting CO_2. In other words, the total costs (including the expected profits) for capturing, transport and storage must not exceed the tax and quota savings.

5.1. Value chain costs based on interview series

As to capturing of CO_2, the series of interviews indicate a large variation in the estimated costs, and for some of the respondents these costs are a part of their competition parameters, which they do not wish to disclose. Two of the Danish respondents have indicated an estimated pricing for capturing of CO_2 to 300-400 DKK/ton and 500 DKK/ton, respectively, where one of the suppliers of the total value chain indicates costs of approx. 80-130 DKK/ton. Rambøll has previously published a report with price calculations for capturing CO_2 from a Danish waste incineration plant of approx. 345 DKK/ton[8], which corresponds well with the information acquired in these interviews. However, it must be mentioned that the costs for capture may vary greatly depending on the scale and complexity of the flue gas.

The costs associated with the storage of CO_2 are indicated by the respondents to be approx. 200-300 DKK/ton in the build-up phase of CO_2 storage infrastructure, with an expectation that the cost can be reduced to 50-100 DKK/ton in the long term. The price lies in the same range that is expected from British storage facilities when the infrastructure is developed. The expected costs for these are around €6-20/ton (45-150 DKK/ton)[9].

When calculating the transport costs, it is important to consider the entire transport from capture to storage, which includes both land transport from source and possibly maritime transport. Some respondents have provided an estimate of the total costs between 115 DKK/ton and 900 DKK/ton. The great variation is due to, among others, the large variations in price for transportation to the place of shipment, depending on the type of transport and distance. If land transport is carried out in pipelines, which are planned in Northern Jutland, the costs at this stage are expected to be at 80-200 DKK/ton, while corresponding transport by truck would have a cost at around 150-200 DKK/ton.

Many actors within the field estimate the total costs through the entire value chain to be at approx. €100-€200 (750-1500 DKK) per ton CO_2. AKER, Dan Unity, Danish Shipping (Danske Rederier) expect that it can be done for between €80-€100 (600-750 DKK) per ton, while Horisont Energy have a goal that it can be done for approx. €150-€200 (1120-1500 DKK) per ton.

The summary of responses regarding the cost structure for the entire CCUS value chain is provided in Table 2 below:

[8] Rambøll - CO_2 Fangst på danske affaldsenergianlæg
[9] Zero emissions platform – The Costs of CO_2 Storage

Table 2: Summary of costs for CCUS based on interviews

Operation	Cost	Comments
Capture	80-500 DKK per ton	Expected high price in short term with great potential for lower costs in long term
Transport	115-900 DKK per ton	Total price depends considerably on the source location and the costs related to transportation by land
Injection	50-300 DKK per ton	Prices around 50-15 DKK/ton expected in long term
	245 →1700 DKK per ton	Short term: 1000-1700 DKK per ton Long term: 600-1000 DKK per ton

5.2. Cost analysis for maritime transport of CO_2

As a supplement to the conducted interviews, a cost analysis for the maritime transport of CO_2 has been created. The analysis has been performed on two cases – one on a ship that can transport 22,500 m^3 of CO_2, and another ship that can transport 7,500 m^3 of CO_2, corresponding to 25,000 tons and 8,000 tons of CO_2, respectively. For both cases, calculations are done for scenarios where these ships are also able to transport LPG.

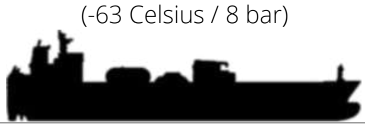
The analysis is a simple cost analysis, where one looks at operational cash flow including earnings, OPEX, fuel costs and other related costs for operating a ship on a specific route. This does not include the ship financing structure, and how much money the ship can earn after the expiry of the contract. For each case, the calculation has been based on two scenarios: a 15-year and a 20-year contract with a fixed volume from the emitter. At the end of a 15-year contract, two additional scenarios have been considered: 1) the ship has been scrapped and the steel value for the ship has been received, and 2) a cash sale of the ship, where it can continue its operation as an LPG or CO_2 ship. For the 20-year contract, only the scenario with the scrap value has been taken into consideration as it would not be commercially attractive to purchase a 20-year-old ship when looking at the average lifespan of ships.

Prices for building new ships that support the calculations were discovered by talking to companies who are active on the CCUS market, and by benchmarking with ships that share the same characteristics. As this is still an early stage, it can be expected that the prices for building new ships may change as the market develops, steel prices fluctuate and as shipyards gain experience with these types of ships. Prices for building new ships, as shown in the cost analysis below, have been affected by the current high steel prices and long order books that take up place at the shipyards, which means that historically speaking one lies in the high end of the price index. Price fluctuations will affect the final cost analysis, but they will not change the overall conclusion, and thus the figures may still be used as a point of reference.

In addition, it has been assumed that fuel prices are as shown in Table 3, and that ships can sail on Marine Gas Oil (MGO) with a low sulfur content and High Sulfur Fuel Oil (HFO) with higher sulfur content. As the ships are subjected to EU regulations when sailing in EU waters, a differentiation is made between these two types of fuel. About a fifth of the selected route is in areas, where it is required to sail with a more expensive MGO. Also, it is important to note that the assumed fuel prices have a significant impact on the ship operating costs. Historically, the fuel prices have been volatile and thus any fluctuations will affect the final cost analysis. This also clarifies the purpose of the analysis as being a base-case analysis that can be used as a reference. Table 3 below sums up the main assumptions made in the described cases.

These assumptions have been verified by Maersk Broker who has more than 30 years of data and information on ship operating costs.

Table 3: Summary of main assumptions in the two cases for cost analysis.

	Case 1	Case 2
Ship types: (Pressure / Temperature)	22,500 m^3 (-63 Celsius / 8 bar) 	7,500 m^3 (-35 Celsius / 19 bar) 
Price for building new	68m USD / 519m DKK	52m USD / 397m DKK
Scrap value	3.16m USD / 24.1m DKK	1.68m USD / 12.8m DKK
Route distance / round trips per year	800nm / 41 round trips	800nm / 44 round trips
Fuel prices	HFO = 550 USD per ton / 4,200 DKK per ton MGO = 1,050 USD per ton / 8,022 DKK per ton	

The calculations for individual scenarios are based on the method of finding a minimum rate at which the project pays back for itself. This means that the analysis result does not include the investors' requirements for return on investment, which also means that the values below must be viewed as the absolute cost that can be required by maritime transport of CO_2 under the specified assumptions.

Lastly, it is important to emphasize that the analysis is based on the fact that all costs related to the operation of the ship (price for building new, OPEX, bunker, port costs, etc.) are covered by the ship operator, and the minimum rate will be adjusted for these.

The achieved results based on the assumptions above have been shown in Table 4 and Table 5.

Table 4: Base-case for a 22,500 m³ CO_2 ship

22,500 m3 VESSEL	Contract duration: 15 years	Contract duration: 20 years
Scrapping after contract	14.3 USD / 109 DKK per ton CO_2	13.3 USD / 102 DKK per ton CO_2
Commercial opportunities after contract	12.98 USD / 99 DKK per ton CO_2	N/A *(not seen as a commercial opportunity)*

Table 5: Base-case for a 7,500 m³ CO_2 ship

7,500 m³ VESSEL	Contract duration: 15 years	Contract duration: 20 years
Scrapping after contract	31.8 USD / 243 DKK per ton CO_2	29.1 USD / 221 DKK per ton CO_2
Commercial opportunities after contract	28.6 USD / 219 DKK per ton CO_2	N/A *(not seen as a commercial opportunity)*

When comparing the two analyses made in this report, it is possible to see that for a ship with cargo capacity of 22,500 cm^3 the CO_2 the costs lie in the range of 99-109 DKK per ton CO_2. For a ship with cargo capacity of 7,500 m^3 the CO_2 the costs are 219-243 DKK per ton of CO_2. To put the figures in the analysis into perspective, the interviewed parties indicated that the price for maritime transport of one ton CO_2 is between 115-383 DKK. However, this price range is without specified ship sizes or assumptions in the estimate, which means that the comparison between the analysis above and the estimates from the interviews cannot be compared one to one. Thus, it is not surprising that the figures from the cost analysis lie in the lower end of the estimates from interviews. Consequently, this cost analysis should be used only as a reference for the cost of maritime transport to a higher degree compared to what can be charged on the market.

Another perspective on the results obtained from the cost analysis may be found in a study from 2021, where transport costs for CO_2 were estimated based on the Northern Lights project in Norway.[10] Here, the price was estimated to approx. 35 USD (268 DKK) per ton of CO_2, which corresponds to the results shown in Table 5. The reason why the cost analysis results are slightly higher than in the study can be related to the fact that the price for building new ships for the Northern Lights project is higher than assumed in the report, as the ships have installed LNG engines, air lubrication systems and wind-assisted propulsion systems to reduce the emissions of CO_2. This has resulted in a higher price for building new ships compared to the "standard" CO_2 ship of the same size.[11]

[10] Smith, Erin & Morris, Jennifer & Kheshgi, Haroon & Teletzke, Gary & Herzog, Howard & Paltsev, Sergey. (2021). The Cost of CO2 Transport and Storage in Global Integrated Assessment Modeling. SSRN Electronic Journal. 10.2139/ssrn.3816593.

[11] https://shippingwatch.com/suppliers/article13359295.ece

Table 6: Overall assessment of costs for CCUS based on interviews and cost analysis.

Operation	Cost	Comments
Capture	80-500 DKK per ton	Estimated high price in short term with great potential for lower costs in long term.
Maritime transport	100 – 375 DKK per ton	Total costs depend here on many assumptions incl. Route and size of vessel.
Land transport	80-200	Pipelines or truck
Injection	50-300 DKK per ton	Prices around 50-150 DKK/ton are expected in long term
	310 →1250 DKK per ton	Short term: 700-1250 DKK per ton Long term: 310-900 DKK per ton

5.3. Overall financial incentive for establishing a CCUS value chain

In June 2022, the Danish government agreed on a green tax reform, where a combined quota and tax payment was passed per ton of emitted CO_2. The payment varies depending on the company type. Companies subject to quotas in the European quota system, which do not carry out mineralogical processes, must pay 1125 DKK per ton CO_2. Companies which carry out mineralogical processes must pay 875 DKK ton of emitted CO_2. These figures are based on an estimated European quota price at 750 DKK in 2030.

In case of the above tax rates, there will be a gain from capture and storing CO_2 if the cost for this is below DKK 1125 per ton CO_2 for companies subjected to quotas, and below DKK 875 per ton CO_2 for mineralogical processes. As shown in Table 2 and Table 6, the total cost of CO_2 storage is not expected to exceed the quota price. If the total price for capture, transport, and storage does not significantly exceed DKK 1000 per ton CO_2, it will be a good business case on CCUS for companies subject to quotas already now if they cannot reduce their consumption of fossil fuels in a less expensive way. For the mineralogical companies, it will require that the costs for CCUS are below DKK 875 per ton CO_2 for them to be worthwhile to participate in CCUS, which currently creates doubt as to whether CCUS will pay off for mineralogical companies. However, it is worth mentioning that mineralogical companies, such as Aalborg Portland, have very few cheaper alternatives to readjust their concrete production than CCUS. Furthermore, it can be expected that the price for CCUS will most likely be in the lower end of the price scale as shown in Table 2 and Table 6 due to the large volumes of CO_2 a concrete plant emits. The green tax reform has opened for opportunities to secure the economy in connection with CCUS investments for companies using fossil fuels. However, this reform has not created an incentive for capturing CO_2 from sources that emit biogenic or combined fossil and biogenic CO_2, as the reform only covers the usage of fossil fuels. These companies include, among others, waste plants, biomass-driven cogeneration plants and biogas plants.

The business potential at European level depends on the national incentive mechanisms (fees), as well as European quota price dictated from EU's Emission Trading Scheme (ETS), which at the time when this report was written had a price of approx. €65 (485 DKK). As shown in Figure 3, the price has been increasing steadily over the recent years, and Future markets suggest that this trend will continue during the coming years. [12]

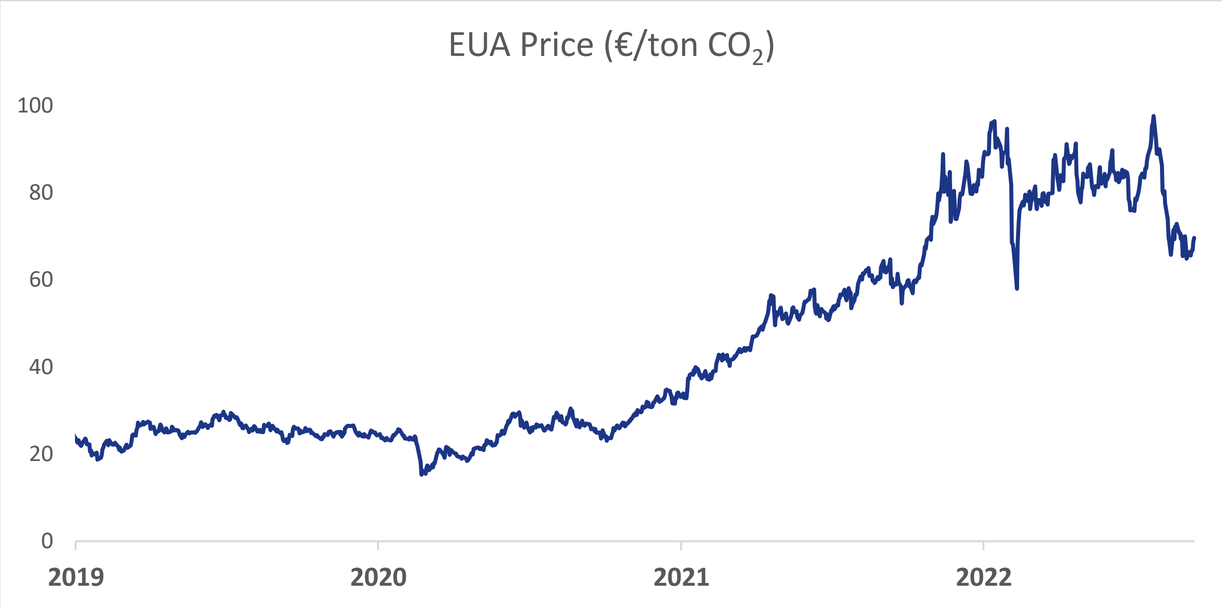


Figure 3: Price development for CO_2 quotas (EU ETS)

6. Alternatives and barriers (other forms of transport / competition / infrastructure)

When storing CO_2 in former oil and gas reservoirs, another alternative to maritime transport will be available - the establishment of new pipelines or the use of a former gas infrastructure. This alternative will, however, be highly dependent on the distance to the coast and the existence and status of the current infrastructure. If new pipelines must be established to offshore reservoirs, it will require significant investments. The assessment in relation to Greensand is that it would require volumes of 4-8 Mtpa in the region for this solution to be profitable. For example, this can be seen in the Dutch projects, where the used reservoirs are located relatively close to the coast, and the gas production has stopped, so that the existing gas infrastructure can be reused for the storage of CO_2 in these reservoirs. In this case, a large supply of CO_2 must be shipped out to those port facilities, from which it will be pumped into the reservoirs. Unless these volumes can be secured locally, it will be necessary to transport CO_2 to these "hubs". Some parts of this transportation can/will go through onshore pipelines or, for example, barges, but parts of the transportation may come from sources without access to pipelines, which is why it may become relevant to introduce maritime transport. EcoLog supports this in their interview:

> *"There are a lot of emitters that are located far away from storage fields. At certain distances, ships are cheaper than pipes."*

[12] https://tradingeconomics.com/commodity/carbon

When it must be decided whether to use vessels or pipelines, this will depend on individual scenarios and the type of infrastructure that is already available. Many studies have been carried out on break-even distances for different transportation volumes of CO_2, and pipelines generally do have an advantage for large volumes and relatively short distances, while transport by ship allows greater flexibility and advantages especially for longer transportation and smaller volumes[13]. For transport (port-to-port) of 0.5 Mtpa, transport by ship will become less expensive already for 160 km, while it would be 500 km for 5 Mtpa.[14] Additionally, ships provide a greater flexibility for incrementally increasing or decreasing the capacity if the demand changes.

No matter how the value chain is put together (capture, transport, utilization, and storage of CO_2), a high degree of standardization is necessary, especially in relation to the interfaces between each step in the value chain. Here, standard requirements for transport (pressure, temperature) and quality must be established for the transported CO_2. If the total cost through the value chain must be reduced, one of the greatest challenges, among others, is the pressure regulation during the transport chain, as this regulation is very energy intensive. If this becomes difficult to ensure across the value chain when using the existing pipelines, it will become yet another argument to build new ships, as custom-built ships have flexible pressure regulation, which could lower the costs across the value chain.

7. The role of maritime transport in CCUS value chain

Maritime transport will have a significant role in the creation of a commercial CCUS value chain. Maritime transport is a good solution in the short term because it is cheaper and faster to expand a maritime infrastructure compared to establishing new pipelines. At the same time, in the early stages of establishing the market and value chains for CCUS, it can be necessary to have flexibility in the infrastructure – a flexibility that the maritime transportation will be able to ensure. Currently, only a few ships sail with CO_2, and those that do are relatively small. The actors in the shipping industry do not see any technical barriers for the maritime transport of CO_2 on a large scale to be more difficult than the transport of other gasses which are today transported by ships.

These interesting perspectives in the growing CO_2 market have generated interest from several actors within the maritime industry. From a European perspective, a handful of shipowners have announced their interest and/or have engaged actively in establishing themselves on the market for maritime transport of CO_2. This involves already established gas carriers such as Exmar and Knutsen OAS to new companies with background in gas transport, such as Ecolog and Dan Unity. Furthermore, some interest has also been observed from several Japanese multi-shipping companies such as MOL of NYK as well as Danish tanker company Torm, which has traditionally transported refined oil products. Despite the interest from several actors, only a few have committed to the market and ordered new ships. Here, a joint venture of oil majors (TotalEnergies, Equinor and Shell) are the only ones who have ordered two 7,500 m^3 vessels to be used in the Northern Lights project. Furthermore, several shipowners have had their ship designs in different sizes approved by the classification companies.

[13] Applied Energy 287 (2021) 116510: A review of large-scale CO_2 shipping and marine emissions management for carbon capture, utilisation and storage
[14] Element Energy; Shipping Co2 – UK Cost Estimation Study 2018

The lack of ship orders is mainly due to commercial and technical risks that must be solved before companies are willing to invest. The next section deals with the technical and commercial considerations of maritime actors and what needs to be changed before a market for CO_2 shipping can be established. This will be followed by a section that describes what the future of CO_2 shipping could look like. These sections are based on the second round of interviews, where the interviewees are companies that have publicly announced their interest in maritime transport of CO_2.

7.1. Commercial opportunities

The role of shipping in the value chain

In the short term, all interviewed parties agreed that shipping will not be able to play a significant role without being a part of a consortium. Dan Unity, Ecolog and Torm – all agree that the first projects will require custom-built ships that fit into the surrounding infrastructure, and that are adapted to the estimated transport volumes for capture and storage in these projects. Since building these ships involves a considerable risk, the shipping contracts must be based on the underlying contract between capture and storage facilities. The duration of these contracts is expected to be 10, 15 and 20 years depending on the ship and the project. According to Lars Mathiasen, VP at Torm, there are "no shipowners who would order custom-built ships without long-term contracts". This is back up by Paul Taylor, Global Head of Societe Generale's Maritime Industries, who are experts in financing maritime infrastructure projects. Paul Taylor believes that "high quality sponsors" with strong credit background and a history of being able to execute similar projects is necessary to be able to support the project and thus raise long-term capital for an integrated CCUS value chain. Societe Generale state that it is crucial for the financing of the project that the risk is distributed and managed in all parts of the value chain – from emitter to storage, as banks like this must be able to ensure that the project can continue even if one part violates its obligations. This is an area that the commercial parties across the value chain should focus on early in the negotiations.

The views are deviating among the interviewed parties as to which vessels are most efficient for CO_2 transport. Ecolog have an ambition to build ships in specific sizes and offer their operations as a service. Jasper Heikens, Chief Commercial Officer of Ecolog, mentions that the costs should be as low as possible, because CO_2 is a waste product, and its disposal must be profitable. Ecolog believe that the most obvious way to reduce costs is through a scale as larger ships result in lower costs per ton. Lower costs per ton, driven by increased capacity without increasing the price for building new ships, are shown in the figures in section 5.2. This is also the reason why Ecolog are considering ships with cargo sizes of 25,000 m^3 and 84,000 m^3 with the latter being much larger compared to competitors.

Where Ecolog has strong focus on the size of the vessels, Torm are neutral in relation to sizes. Torm do not believe that a shipping company should lock their focus on the size only, but instead look at the project itself and build a ship that best suits the surrounding infrastructure. If a profit is made that satisfies the investors, it is possible to have a pragmatic approach to communication with the rest of the value chain.

This discussion is also reflected in the question of whether the ships themselves should be as CO_2 effective as possible. Ecolog sees this as a "license to operate" and believes that it will be difficult to communicate to customers about their green transition without being ambitious about it. Both Dan Unity and Torm believe that it will be good to have "green" ships to transport CO_2, but they would not make this as a requirement, unless it is required by a specific project that ensures financing as well. In other words, the freight rate must be able to cover the premium of the price for building new ships for an energy-efficient ship that can potentially sail on alternative fuels.

The different viewpoints among the interviewed parties indicate a beginning of a divergence in the business models with two primary directions:

1. A pragmatic approach, where vessels are built for a specific project. Here, shipping plays a passive role and adjusts to the rest of the value chain.
2. A proactive approach, where a company has a clear position on how to build ships that can be used across several projects and locations. Here, the shipping company plays a self-determining role and fins projects where their ships fit best.

Risks and barriers
The respondents in the second interview round all agree that the greatest barrier for being able to invest in ships is to find a partner who is willing to enter a long-term contract. Without contracts for capture and storage between strong and experienced partners, it is highly unlikely that shipowners will build CO_2 vessels, as in this case it would only be based on speculation.

The three main reasons why emitters will not sign such contracts at this moment are as follows:

1. Costs for capture, storage, and transport have been higher than the costs related to emissions of CO_2 into the atmosphere. This is, among others, due to a lack of a tax structure that has ensured sufficient commitment to investments in the necessary infrastructure or technology to avoid these emissions. With the green tax reform of June 2022, it is no longer an obstacle in Denmark. In Europe, which is subject to Emission Trading Scheme (ETS), the price for emitting CO_2 has increased during the recent years, but there is still no guarantee that this will remain stable and high enough to be able to justify entering a long-term contract.
2. Carbon Capture on a large scale is still rather immature and expensive. The emitter faces a relatively great risk that the establishment of CO_2 capture and subsequent transport and storage or utilization cannot be done at a sufficiently low (and safe) price.
3. There is fear of committing to deliver a certain amount of CO_2 over a long period of time. Emitters can quickly face a "lock-in" effect, where one has made a commitment to dispose CO_2 at an expensive price versus other less expensive alternatives in the future.

These are real concerns, and according to Societe Generale's Maritime Industries, the risks of CCUS value chain and economy should be analyzed from a holistic perspective, where the focus is on the entire value chain. For the first emitters to sign contracts and start projects, the national authorities must set up clear frameworks for this industry and contribute to minimizing risks associated with the project, for example, by financing parts of it. According to Paul Taylor, it will be difficult to finance projects on a “non-recourse” basis, where lenders only have the right to the cash flow from the project if there is no “take-or-pay” agreement in place.

In other words, projects must ensure that cash flows are visible and predictable if long-term capital is to be raised from both equity and debt. The French bank also emphasizes that certainty around CO_2 price is essential to make the project attractive. This can be achieved by (i) implementing a CO_2 tax that is higher than the cost of CCUS, what Denmark has already done, or (ii) in regions subject to ETS, the emitter can enter “Contracts for Difference” (CfD) with the government, which guarantees a long-term price if CO_2 based on a pre-defined volume that can ensure the project’s returns. A CfD has been recommended in Great Britain and is based on an instrument with which the Danish government has previously been very successful with in expanding the Danish wind industry.

Other barriers specific to shipping include missing permits for transportation of CO_2 across national borders. Currently, CO_2 is classified as a waste product under London Protocol, which means that it is practically not allowed to transport CO_2 across national borders. However, it turned out to possible to enter into bilateral agreements between countries that makes it possible to transport CO_2 between these countries. In September 2022, the first agreement was concluded between the Netherlands and Norway allowing the transport of captured CO_2 from Yara fertilizer production in the Netherlands to Northern Lights storage facilities in Norway. In addition, a bilateral agreement has been concluded between Denmark and Belgium, which enables storage of Belgian CO_2 in the Danish underground. Therefore, it can be assumed that this will not be a visible barrier moving forward, and that the London Protocol will be looked at critically as the CCUS market develops.

7.2. Technical observations

As previously described, the profitability of using ships instead of pipelines depends partly on the actual volumes to be transported and partly on the distance.[13] Thus, these considerations will also play a role in relation to the relevant ship dimensions. In the interviews, it is mentioned that the northern European projects will focus on the use of medium-sized ships. Here, Dan Unity focus on ships in sizes between 10,000 m^3 and 25,000 m^3 for use in the local North Sea, while Torm also mentions the need for ships of the same size. With a local catchment of captured CO_2 for transport of 3 Mpta tons (or 2.25 million m^3), with a ship size of 20,000 m^3, it would correspond to approx. 110 ships per year or one ship every 3 days. With a total time for loading in Aalborg, discharge at a field in the North Sea and return of approx. 3-3.5 days, this distance could be serviced by two or three ships.

However, these considerations would be different for longer transport, and it may be necessary to choose a larger vessel. In these cases, Ecolog consider ships with a capacity of up to 84,000 m^3. This type of ships would be especially suitable when the CCUS market is better established, and where it is expected to transport the captured CO_2 from regions that do not have access to utilization or storage. This type of ships would also become relevant for transporting large volumes of CO_2 to areas with inexpensive energy, where the establishment of larger PtC facilities can be expected.

To ensure as much cargo on board as possible, Dan Unity works with design criteria as close to the triple point for CO_2 as possible. This is partly because the lower pressure gives an opportunity to design ships that are significantly lighter, and partly because more CO_2 can be loaded per m^3, as the density of liquid CO_2 is higher than the low-pressure regimes. In fact, it would be limited to a maximum of 12,000 m^3 CO_2, if one wishes to operate with medium pressure (approx. 15 bar). The criteria discussed in the interviews are 6.5 bar and -45°C, and 8 bar and -15°C, respectively. Exactly at these pressure and temperature regimes, where one approaches the triple point for CO_2, extra attention must be paid to impurities in the pressurized CO_2. This is because any impurities can move the current triple point, thus risking the formation of dry ice, for example, in case of expansion in pumps and pipes used to move CO_2 in and out of the tank systems. However, the concern about this is not pronounced in the shipping industry, as similar problems are known from LNG.

As to the local buffer tanks at port facilities, it is expected that these must operate under the same pressure and temperature regimes as expected in the maritime transport. To ensure a fast loading of ships at the port facilities, it is required that the size of the local buffer systems is at least of the same volume as the ships using the facilities. To ensure operational flexibility, different safety margins are discussed in the literature, but based on the experiences gained from LNG transportation the local capacity of 120% is a good compromise between flexibility and costs.

To establish local buffer facilities, several safety-related aspects must be considered. Even though the industry holds extensive experience with handling other acutely toxic and flammable gases, there are still some safety aspects that must be considered for storing of CO_2, especially in urban areas.

Today, it is expected that investing in ships for transportation will require long-term contracts with consortia, which are based on capture and storage facilities within these consortia. This may constitute a risk that solutions are developed specifically towards the individual value chain. Here, it is worth noting that if a more liquid spot market for maritime transport of CO_2 must be developed in the long term, it would be extremely relevant to define a common standard for those pressure and temperature regimes that must be transported, so that more operators can use the same port facilities.

7.3. Future market for CO_2 shipping

Several actors from the maritime industry are showing interest in transporting CO_2 in the future. However, very few have entered contracts and ordered vessels at the shipyards, which provides good opportunities for new participants to enter the market. Whether the potential is greater for certain shipowners to get involved will depend on what a future scenario for CO_2 shipping will look like in the short and long term.

Relevant actors
Companies such as Dan Unity and Ecolog, which both deal with maritime transport of gas, are known for deep and specialized technical knowledge within building and operating exactly these types of ships. This is because gas ships include advanced technical specifications such as cooling systems or tanks with different pressures. Companies that operate in these segments often have their own departments and competencies within this area. In case of gas transport, it is usually LPG or LNG. Here, LPG ships will highly resemble the specifications of the future vessels for CO_2 transport, as they are usually operating at higher pressures, whereas LNG ships typically operate with cooling to very low temperatures to

ensure that the gas is transported in liquid form. Therefore, with the right specifications, it will be possible to sail with both LPG products and CO_2 on the same ships, which means that LPG shipowners may be considered as high-potential actors, if looking at the competences and resources required to operate CO_2 ships.

As stated earlier in this report, it is not expected that it will become difficult or more complicated to transport CO_2 compared to other gas types. Thus, this means that shipowners who are already involved in the transportation of gas have the necessary technical resources, and thus will not face radical organizational expansions, changes, or costs. This means that there will be a considerable synergy between the existing business and the future transport of CO_2. Also, the engagement in maritime transport of CO_2 for other segments, for example, dry cargo shipowners, means that the companies must build up competences in those areas where they do not have enough experience yet.

The product tanker company Torm have shown interest in playing a role in the establishment of a market for maritime transport of CO_2. Tanker companies such as Torm rely typically on advanced technical competences but deviate from the level of complexity associated with gas transport. If a tanker company would step into this market, they would have to build up competences and knowledge within the transportation of gas types, but from an organizational point of view they would have more experience in handling similar technical problems and processes. In addition, the speculative aspect in this could be whether tankers, which are currently driving business based on the transportation of liquid-based fossil fuels, seek new markets in line with the green transition.

Competition situation

Today, there are approx. 40 gas carriers in the world with a fleet of more than 10 vessels. These companies can be classified as potential candidates for maritime transport of CO_2. 20 out of these 40 companies are active in the LPG segment, where they are seen to have a great potential for being able to expand their services to include CO_2. Current observations show that there is a predominant tendency for European-based gas companies being the first ones to invest in the maritime transport of CO_2. Approx. 30 out of these 40 gas carriers are companies with headquarters in Europe, and approx. 20 of these companies have important operations in countries bordering the North Sea.

With many gas carriers who can potentially use their existing competences to enter the CCUS value chain, this could indicate that the future market will be characterized by competition. If you include other actors, including oil majors and tanker companies, this will become even more pronounced. This would apply both in the North Sea but also in other regions that must develop a CCUS value chain.

Future perspectives

Since the CCUS value chain is still in its early stages, and the upcoming projects are still a "proof of concept", it is expected that the first ships will be ordered on long-term contracts. Such a market will highly resemble about the beginnings of the LNG market, where vessels were specially designed for the project, and the assets in the value chain were financed from the entire value chain. Those projects that are most advanced in the North Sea are expected to use middle-sized vessels that can sail between A and B in shuttle service for 10, 15, or 20 years. Since the projects will have pre-defined capture and storage facilities, this will support the pragmatic business model that both Dan Unity and Torm are relying on, as the project and its finances will define the ship's design specifications.

Also, it is expected that in the short run the ships will transport CO_2 only for storage and not for utilization. This will support a business model with long-term contracts within a consortium, as the volumes are already known for the captured CO_2 to be stored. Only with more customers and a larger scale of capture, storage, and possibly utilization, a spot market can be expected to be created for transport of CO_2. This also supports the business model with medium-sized ships, as ships of +50,000 m^3 would not make sense before there is a need for transportation of CO_2 across the continents.

According to most of the maritime actors, it is important to have long-term contracts from a consortium before they can build and finance the first vessels. This will be necessary to kickstart the market and show that it is commercially more profitable to store CO_2 rather than to pay a CO_2 tax. However, long-term contracts between pre-defined capture and storage facilities create a "lock-in" effect. Let us look at Aalborg Portland, a Danish concrete company who plan to be ready to capture CO_2 in 2026. If they sign a 20-year contract, they will have an obligation to deliver the same volume of CO_2 in 2046 as they do now. Due to the scale of concrete production, a CCUS would probably be the cheapest solution for Aalborg Portland to become CO_2 neutral in 2050. However, this is not necessarily the case for all industries and certainly not for all individual industrial facilities.

To avoid the lock-in effect for most of the heavy industry in Europe, the long-term contracts should only be used wherever it makes sense in the long run. Hence, it would be obvious to focus on the long-term contracts in industrial clusters or "CO_2 hubs", where larger volumes can be collected. Here, larger ships with more "neutral" specifications would be preferable, which would support the more proactive business model. However, larger volumes open for the possibility that ships will become less attractive than pipelines if CO_2 must be transported by land to large hubs. Even in the long run, in a market characterized by concentrated CO_2 hubs, shipping, according to Ecolog, will have three advantages compared to pipelines. First, it is easier to add or remove capacity from ships in line with the existing demand. Second, ships create greater reliability as it is easier to add an existing ship to a route compared to repairing or building a new pipeline. Third, emitters in an established market will have the opportunity to choose the storage facility with the lowest price, which will lower the price across the value chain.

Danish shipping

Among the Danish actors who show interest in the transport of CO_2, Dan Unity and Torm are the most advanced within the field. In short term, they will have an advantage to the transport of CO_2 in projects in Denmark or the North Sea as they will have access to the right stakeholders in the relevant consortia. An example here could be that Dan Unity have reached Phase 2 in Greensand project[15]. One can argue that if the market is based on long-term contracts within consortia, it can be expected that first movers will enjoy an advantage in the future tenders if they have already shown that they can deliver maritime transport based on one to two contracts. Here, both Danish actors will have an advantage with their pragmatic business model, where ships are specially built for the projects.

That said, shipping has historically never been a market where first movers could easily maintain their leading position in the market shares. As mentioned before, transporting CO_2 is not very different from transporting other types of gas, and thus competitors will be able to enter the market easily. In addition,

[15] https://www.projectgreensand.com/

companies from other segments with an interest in the growing market with a "green potential" can also become future competitors, which increases the possible rough competition.

Denmark is a country with a remarkable representation of large and medium-sized shipping companies within gas and tankers, and they may become relevant in a future CO_2 transporta scenario. This is especially valid for companies that already today are moving into the LPG segment of gas transportation. Naming the Danish shipowners or operators who would be able to take part in the maritime transportation of CO_2 would be highly speculative and unjustified. However, there is a great potential for the Danish maritime actors to participate in the development of the new market when looking at the potential of the Danish maritime environment, which is characterized by innovation, extensive knowledge, competencies, and a geographical location close to the global epicenter of the first CCUS value chains.

Although it will be difficult to maintain the advantage of being a *first mover* in the long run, the Danish actors have a good position to win the first tenders and sign contracts with the large consortia. If the Danish players will win the first contracts, they will have experience and access to customers for a long time. From here, they will be able to change their business models easily, so that they can focus on larger and more "neutral" vessels that can compete in the spot market. Therefore, the Danish maritime actors are well-positioned to play a major role in the development of CCUS value chain. This said, the size of that potential will depend on who wins the first contracts, and here it will be easier to maintain the competitive advantage longer the sooner the Danish CCUS projects are initiated.

8. Conclusion: CO_2 value chain from a Danish perspective

Carbon, Capture, Utilization and Storage (CCUS) is set to play a decisive role in the green transition, as it can help ensure a gradual phase-out of CO_2 emissions from existing infrastructure. Historically, CCUS has been used only in a few cases, and currently there is not a large market for CO_2. During the recent years, the increased green ambitions from large companies and the introduction of higher CO_2 taxes has made CCUS more interesting, especially for actors in the North Sea. Today, Denmark together with Great Britain, Norway, Iceland, and the Netherlands are the leaders within CCUS, and the first large projects are expected to be in full operation already before 2030.

In Denmark, CCUS is crucial to reach the target of reducing CO_2 emissions with 70% by 2030, corresponding to approx. 10 Mtpa. The report shows that the total capacity from three Danish CCS projects will ensure sufficient storage capacity to cover this need, especially the approx. 7 Mtpa planned to be captured in Copenhagen and Northern Jutland. The same conclusion can be made on a European level, as the storage capacity in the North Sea is large enough to accommodate the planned volumes from capture facilities in the leading countries. The green tax reform of June 2022 determined a combined quota and tax payment of DKK 1125 per ton CO_2 for companies subject to quotas, and DKK 875 per ton CO_2 for companies carrying out mineralogical processes. The green tax reform has opened for opportunities to ensure financial incentive with CCUS investments for companies that use fossil fuels, if the price for capture, transport and storage can be approx. DKK 1000 per ton CO_2. In cases where the cost is low enough, as it is already now on the Danish market, CCUS would be a good business case for companies subject to quotas. However, the same conclusion cannot be drawn on European level, where the current CO_2 tax, which is a part of the EU ETS system, is slightly lower and volatile.

The development of a new CCUS value chain will require new infrastructure for both Danish and European projects. Here, additional infrastructure will be required such as pipelines, tank trucks, and port facilities to make maritime transport of CO_2 possible. Maritime transport can play a decisive role in the development of a new infrastructure in projects with longer transportation distances and smaller volumes. In addition, the new custom-built ships can ensure greater flexibility in relation to pressure regulation across value chains as to new or existing pipelines. In this report, the cost analysis showed that maritime transport constitutes a relatively small part of the total costs across the value chain, whereas capture makes up the largest part. Thus, it would be beneficial to include maritime transport in the value chain for projects with no existing infrastructure for this purpose.

Despite the benefits of maritime transport of CO_2, there are no ships ready to transport CO_2 yet. Although many shipping companies have expressed interest in building and operating CO_2 ships, only one order for two vessels has been made for the Northern Lights project. Based on the interviews conducted in this report, it can be concluded that the ships will not be built or financed unless long-term contracts and maturity across the value chain is ensured. The report also concludes that to be able to attract long-term capital the projects must be analyzed across the entire value chain instead of focusing on the individual parts, and that shipping contracts must be supported by long-term contracts between capture and storage facilities.

If a shipping company can secure long-term contracts, they will start out by building custom-made ships designed exclusively for the project. Much like the LNG market in its early stages, the market for maritime transport of CO_2 will be based on long-term contracts with pre-defined capture and storage facilities. This will be the case until a larger scale and more locations for capture, storage, and utilization both in the North Sea and on an international level have been reached. This report has also shown that, despite the great potential for utilization of CO_2 for production of synthetic fuels for, among others, the shipping industry, in the short term the utilization of CO_2 will not play a significant role. This is because the value chains for utilization of CO_2 are not ready that Power-to-X has a greater focus in the Danish context, and that the new green tax reform has not created an incentive for capturing CO_2 from sources that emit biogenic or combined fossil and biogenic CO_2, as the reform only covers the utilization of fossil fuels.

In the long run, a spot market is expected to appear if CO_2 transport becomes an established market. Here, the ships will be able to operate in several ports and with several storage facilities, where CO_2 can be transported across continents and to regions with inexpensive electricity for cost-effective production of synthetic fuels. All other things being equal, this flexibility will lower the price of CCUS as it will require larger ships and create a more dynamic market. Two Danish *first movers* were among the interviewed parties in this report. Both have a pragmatic business model, where their ambition is to build custom-built ships for specific projects. The Danish actors will have an advantage in offering maritime transport to all projects in the North Sea, who consider maritime transport. This report argues that the Danish actors have a competitive advantage in the Danish projects, as they are already able to engage in a dialog with the large consortia.

In the long term, this competitive advantage may become smaller as the transport of CO_2 is not a new discipline, but rather another type of gas that can be transported by ships. This means that many companies will have necessary competencies to enter this market. Especially in an international and fragmented spot market, the Danish actors will not have a significant competitive advantage apart from an assumed experience and network gained from the first projects in the North Sea. Therefore, this report concludes that the potential to make use of the advantage of being the *first mover* is significantly greater the faster the Danish CCUS projects are initiated. In this case, the Danish actors will be able to benefit from having been visionary early in the development of this market segment.

Appendix 1 – Interview guide

Table 7: Interview guide, round 1

Question	Response (note)
How many tons of CO_2 do you expect to be captured on a yearly basis from **your** company or industry branch?	Company/branch (definition): Potential tons/year:
How many tons of CO_2 do you expect to be stored in the underground in the future?	Scope (country/company/region): tons/year:
Do you have knowledge of any current plans to transport liquid CO_2 by sea?	Scope (country/company/region): Potential tons/year:
Do you have knowledge of current plans for a coordinated capture and utilization of CO_2 in the same location?	Location (country, city, company): Potential tons/year:
How do you assess the time horizon for the measures you are aware of?	Years until start: Years to full scale:
Do you expect a switch from storage to utilization of the CO_2 collected from your company or industry branch?	
Do you know the costs associated with storing CO_2 on the seabed of the North Sea?	If yes: DKK per ton
Do you know the costs associated with capturing CO_2 from land-based facilities?	If yes: DKK per ton
Do you know the costs associated with the transport of CO_2, incl. infrastructure, tank facilities, cooling and land transport?	If yes: DKK per ton or ton-km.
Which alternative means of transportation do you know of? For example, pipelines, road transport, and do you know the price structure related to these?	If yes, which:
What is, in your opinion, a realistic estimate of the value of a ton of CO_2 for utilization as, e.g., PtX?	DKK per ton:
In your opinion, which taxes and subsidies are needed if CO_2 must be transported in large volumes by ship?	DKK per ton:
What technical, legal, and financial barriers do you see in relation to CO_2 transport in large volumes by ship?	Indicate problem/time frame:
Do you see any barriers in relation to the infrastructure if CO_2 is to be shipped from ports?	If yes, what are these:

Table 8: Interview guide, round 2

Question	Response (note)
Who do you see as your primary customer?	Branch: Potential tons/year:
In which situations does the maritime transport have an advantage over the alternatives (e.g., pipelines)?	
What volumes are necessary to draw contracts for CO_2 transport?	Scope tons/year:
Do you see shipping companies driving business alone in the value chain or are consortia needed?	
How long do you expect the contracts to last before it is meaningful for you?	Year:
What should the shipping rates be for it to be profitable?	DKK/ton
What should be the ship size for it to be profitable?	Ton:
Is it a necessity/advantage that ships are green?	
What is the optimal pressure/temperature in relation to ship design? What is the most efficient for the ships vs. what is optimal for the value chain?	
What is your experience with loading/discharge design of CO_2 tankers? What impact will it have in relation to getting involved in the maritime transport of CO_2?	
What technical risks do you see in relation to ship operations?	
What commercial risks do you see in relation to maritime transport of CO_2?	
What risks do you see in relation to CO_2 infrastructure?	
Which barriers do you see as the most important to remove before CO_2 can become a commercial discipline within shipping?	
Will there be a differentiation between commercial operation of fossils and biogenic CO_2?	
What impact will the transition to utilization as an alternative to storage have on the commercial maritime transport of CO_2?	
How do you see maritime transport of CO_2 in the short term (5 years) and long term (10-15 years)? • Customers • Contract types • Geography • Vessel sizes	

Appendix 2 - Respondents

Table 9: Respondents

Company	Location in value chain	Round	Contact
Aalborg Portland	Large source; Experience with volumes and costs upon capture	1	Thomas Uhd
Aalborg Havn	Infrastructure, local storage, and utilization	1	Martin Vogdrup Olesen
European Energy	Utilization, PtX	1	Martin Sloth Jensen
Maersk Zero Carbon Shipping	Total value chain, but primarily transport and storage	1	Johan Byskov
C4 – Carbon Capture Cluster Copenhagen	Total value chain, primary emitter, capture, infrastructure	1	Mikkel Krogsgaard Niss
Danske Rederier	Transporter; Knowledge of Danish initiatives for transport of CO_2	1	Thomas Sylvest
Ammongas	Capture; Knowledge of costs in connection with the capture of CO_2	1	Jonas Samuelsen
Acer Carbon Capture	Capture, with the focus on the entire value chain	1	Anders Rooma Nielsen & Peter Thoft Knudsen
Gas Storage Danmark	Storage	1	Martin Patrong
EVIDA	Land transport	1	Morten Poulsen
Societe Generale	View on the risk across the value chain. Experts in financing of maritime infrastructure	1	Paul Taylor, Mark Westley Chris Wright & James Paton
Horisont Energi	Capture, utilization, and storage	1	Rasmus Holmer
Dan Unity	Maritime transport	1 & 2	Steffen Jacobsen
Ecolog	Maritime transport	2	Jasper Heikens
Torm	Maritime transport	2	Lars V. Mathiasen

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